# Animal mobility in Chalcolithic Portugal: Isotopic analyses of cattle from the sites of Zambujal and Leceia

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## Abstract

This paper outlines the results of strontium isotopic analyses from cattle recovered at the Chalcolithic fortified settlement sites of Castro do Zambujal and Leceia (Estremadura, Portugal).

The Portuguese Chalcolithic (c. 3000-1900BC) was a pivotal time of social and economic change with evidence of increasing social complexity resulting in the formation of hierarchical settlements. With these changes came the emergence of long-distance exchange networks and more complex population movements and interactions. Domesticated animals would have played an important role in these emerging economies, and it is assumed that animals migrated with, and were exchanged by, humans as part of these new networks. While direct evidence of these networks is still limited in this region, new methodologies have the potential to expand our knowledge of animal mobility and exchange. This study uses $^{87}Sr/^{86}Sr$ ratios in tooth enamel to identify potential non-local animals at these two settlements. Results indicate that Leceia may have had a higher proportion of non-local animals than Zambujal and had a wider catchment area for its stock, suggesting variations in settlement economies across relatively short distances in this region. These results have important implications for our understanding of animal management at Portuguese Chalcolithic sites, and the involvement of animals in the emerging economies of the time.

Keywords: Iberia; Zambujal; Leceia; Copper Age; strontium isotopes; mobility; fauna

## 1. Introduction

The Portuguese Chalcolithic (c. 3000 - 1900BC) was a time of significant social and economic change, with evidence of the expansion of complex settlements and exchange networks (cf. Cardoso, 2007; Gonçalves, 1999; Lillios, 1995; Uerpmann, 1995; Valera et al., 2017). Domesticated animals played an important role in these economies, and the archaeological record demonstrates that people commonly raised domesticated cattle, pigs, sheep and goats for meat and secondary products (Harrison 1985; Valente and Carvalho, 2014). It is assumed that domesticated animals moved with humans, and were sold or exchanged by people as part of these new networks. However, direct evidence of these exchanges is still limited in this region. In the last decade, radiogenic isotope studies ($^{87}Sr/^{86}Sr$) have provided a means of identifying migrant human and animals in the Iberian peninsula (Carvalho et al., 2016; Díaz-del-Río, 2017; Diaz-Zorita Bonilla, 2013; Díaz-Zorita Bonilla et al., 2018; Waterman et al., 2014) and elsewhere in the world (cf. Knudson et al., 2016; Madgwick et al., 2017; Price et al., 2015; Zhao, 2015). In this paper we outline the results of new strontium isotopic analyses from cattle recovered from the Chalcolithic fortified settlement sites of Castro do Zambujal (Zambujal) and Leceia (both in the Estremadura region) and use this data to identify migrant animals within these settlements.

### 1.1 Social complexity and exchange networks in Chalcolithic Portugal

The Chalcolithic period in Portugal saw the rise of large ditched-enclosed, fortified hilltop, and walled settlement types. The archaeological record for this time suggests that with the rise of these complex settlements, long and short distance exchange networks emerged (Cardoso, 2003; Gonçalves, 2000; 2001; Jorge, 2000). Alongside these important socio-economic changes there is variation in site type and function, especially between regions (e.g. Cardoso, 2007; Gonçalves et al., 2013); with the establishment of new large fortified sites, mostly in the Estremadura region. The appearance of new types of material culture also in this region, made of materials such as copper, slate, variscite, amphibolite and ivory, has provided strong evidence of the establishment of long-distance exchange networks (e.g. Cardoso and Carvalhosa, 1995; Cardoso and Schuhmacher, 2012; Cardoso et al., 2013: Gauß, 2015; Lillios, 1997; Müller et al., 2007; Odriozola et al., 2010: Odriozola et al., 2013; Roberts, 2008; Schuhmacher et al., 2009; Schuhmacher, 2012; Schuhmacher, 2017). Archaeological data suggests that some of these materials may have been travelling from areas of southern Iberia, or even northern Africa, into the Estremadura region (Schumacher et al., 2009). Using strontium isotopes, a number of studies have now found direct evidence of human migrants into the Estremadura region. The isotopic signature of these migrants indicates that some of them may have also travelled in from areas of southern Iberia (such as the Alentejo region) possibly as part of these exchange networks (Carvalho et al., 2016; Waterman et al., 2014). It is likely that these migrants were bringing domesticated animals with them as they entered new regions, but to date no study focusing on animal mobility in the Estremadura region has been completed.

### 1.2 Animal husbandry in Chalcolithic Portugal

The variations between site types across the region are clearly reflected in the animal remains recovered at settlement sites (Valente and Carvalho, 2014). Fortified sites in the Estremadura region tend to yield large faunal assemblages, dominated by the three main domesticated animals (cattle, sheep/goat and pig), with evidence for the use of secondary products (i.e. milk, wool, and traction) (Cardoso and Detry, 2002; von den Driesch and Boessneck, 1976), whereas smaller unfortified sites have yielded larger proportions of wild species, indicating a different approach to animal exploitation, as part of a more mobile type of existence (e.g. Cabaço, 2010; Correia, 2015; Davis and Mataloto, 2012; Moreno-Garcia and Sousa, 2013; Valente 2013). The two sites included in this study, Leceia and Zambujal, are two of the largest well-known fortified sites in the Estremadura region (Kunst, 2017; Becker and Flade-Becker, 2017). Both of their assemblages show a preponderance of domestic species, with only small proportions of wild species. The use of secondary products, as seen at Portuguese fortified sites such as these, reflects the intensification in animal husbandry seen across Iberia at this time. This intensification has long been linked to the formation of networks for exchanging animals and animal products (e.g. Harrison 1985).

## 2. Strontium isotope ratios and landscapes

The strontium isotope signature of a geographic region is controlled by the nature of the underlying geology (rock lithology) and permeates its landscape and groundwater. This signature is absorbed into the biological tissues of local plants and animals (Faure and Powell, 1972; Gilli et al., 2009). In animals, strontium isotopes are incorporated into tooth and bone through ingestion of water and food. This is due to a physiological process in which Sr substitutes for calcium in the mineral component (hydroxyapatite) of hard tissues (Bentley, 2006; Ericson, 1985; Sealy et al., 1991; Schroeder et al., 1972:496). Unlike carbon, nitrogen and oxygen isotopes that are used in many archaeological studies of prehistoric diet, once incorporated into biological tissues, strontium isotopes do not fractionate (i.e. no change in $^{87}Sr/^{86}Sr$), when passed from prey to consumer. Therefore, an organism's strontium isotope signature directly reflects the bioavailable strontium in its environmental range, rather than its trophic level (Graustein, 1989). Due to how Sr infiltrates biological hard tissues during formation, humans and animals residing in the same territorial ranges and consuming only local plants and animals, should exhibit similar $^{87}Sr/^{86}Sr$ signatures (Tommasini, 2018). In contrast, humans and animals should exhibit differences in strontium isotope ratios between regions that are geologically distinctive. When sufficient geologic heterogeneity is present across regional landscapes, humans and animals can migrate between areas with significant divergences in local $^{87}Sr/^{86}Sr$ values. If animals or humans die and are interred in a location with a marked difference in local $^{87}Sr/^{86}Sr$ values from their own biological tissues, they can be recognized as migrant individuals. This method for identifying migrants has been used productively in many archaeological studies of human and animal migration patterns (cf. Bentley, 2006; Crowley et. al, 2017; Price et al., 2002; Price et al., 2012).

Because using $^{87}Sr/^{86}Sr$ values to identify nonlocal humans and animals requires geologic diversity over reasonably traversable distances, geologically homogeneous regions may limit this method's effectiveness. Portugal and Western Spain exhibit marked differences in geological lithologies, thereby making this region an excellent location to use strontium isotope fingerprinting to study human and animal migration in prehistory. Nonetheless, we must keep in mind that this methodology can only provide a minimum estimate of mobility (minimum number of migrants, MNM), as it is not possible to distinguish between humans and animals who originate from settlements that share similar bioavailable $^{87}Sr/^{86}Sr$ values due to similar underlying geology. Additionally, it is important to note that this method assumes that local populations only consumed local foods and drank from local water sources, as consumption of large amounts of foreign foods can change $^{87}Sr/^{86}Sr$ values (Burton and Hahn, 2016).

### 2.1 Archaeological sites and regional geology

The prehistoric settlement sites of Leceia and Zambujal lie in the Estremadura region of Portugal (Figure 1). The Estremadura is a historically-defined province in the southwestern region of Portugal which encompasses both the Lisbon and Setúbal peninsulas and extends westward to the Atlantic coast. Both Leceia and Zambujal lie close to the coast and to (former) estuaries and interior waterways and, thus, would have been key places for both coastal and interior trade networks.

#### 2.1.1 Zambujal

Zambujal is one of the most prominent and well-known prehistoric fortified settlements in Portugal (Sangmeister and Schubart, 1981). It was occupied from the Chalcolithic period until the early Bronze Age (c. 2900-1700 cal BC), and was subject to several important building phases with a series of walls and other fortifications (Arnold and Kunst, 2011; Kunst, 2010; Kunst, 2018; Sangmeister and Schubart, 1981). Geomagnetic prospections, archaeological surveys and excavations between 1994 and 2013 have indicated that the fortified settlement was larger than previously thought, and is currently estimated at c. 26 hectares (Kunst and Uerpmann, 2002; Kunst et al. 2013; Kunst 2017a; Becker and Flade-Becker, 2017). Material culture recovered from Zambujal suggests that it was permanently settled throughout the 3rd millennium BC and that craft and metal production took place there, likely at a household scale (Müller et al., 2007; Gauß, 2015; Kunst et al., 2016). Additionally, as evidenced by the recovery of raw materials with origins outside of the region --such as copper, amphibolite, ivory and gold - Zambujal was an important center of local and regional exchange networks, (Kunst, 1995; Sangmeister and Schubart, 1981; Uerpmann, 1995; Uerpmann and Uerpmann, 2003).

By the end of the excavations that took place from 1964 to 1973, over 150,000 faunal specimens had been recovered, representing over 95 species. Domestic cattle, pigs and caprines dominate, but wild boar, aurochs and red deer are also present, albeit in comparatively small numbers (von den Driesch and Boessneck, 1976; 1981). Caprines and pigs were the main focus of the domestic assemblage, with smaller numbers of cattle.

**2.1.2 Leceia**

The fortified settlement of Leceia (c. 3500-2200 cal BC), had earlier origins than Zambujal, during the late Neolithic period, but was also abandoned earlier - before the Early Bronze Age. Excavations at the site between 1983 and 2002 revealed a complex settlement fortified by a defensive series of stone walls and towers (Cardoso, 1994; 1997; 2000; 2010). Leceia has received less attention than Zambujal, but its location (elevated above the river Barcarena), its size, and its rich material culture, suggest it was an important regional center for agriculture, material goods, production and trade (Cardoso, 2000). In contrast to Zambujal, there is poor evidence for extractive metallurgy. Neither smelting slags or copper ore were found, but the presence of many copper artefacts, including some which are unfinished, suggest that some copper working was undertaken here (Müller and Cardoso, 2008). Other imported materials, such as amphibolite, have also been recovered, indicating that the site was linked to broader exchange networks (Cardoso and Carvalhosa, 1995; Cardoso, 2004). Faunal remains recovered from Leceia were studied by Cardoso and Detry (2002), and were dominated by domestic cattle, pigs and caprines throughout the period of occupation. Red deer represented the main wild species but, unlike at Zambujal, no aurochs or wild boar were identified. Cattle, pigs and caprines were present in equal proportions during the late Neolithic period but an increase in caprines along with a decrease in cattle was seen during the Chalcolithic period, bringing the overall proportions of these animals broadly in line with that seen at Zambujal. In contrast to Zambujal no isotopic work on either human or faunal remains has previously been undertaken.

### 2.1.3 Regional Geology

The sites of Zambujal and Leceia both lie in the geologically diverse landscape of the Estremadura region of Portugal (Figure 2). The area occupies a portion of the Lusitanian Basin, which is a northern Atlantic basin that was created during a late Triassic rifting phase. In the southeast, this basin connects to the Alentejo and the Algarve Basins and in the north and east it abuts the Late Paleozoic Hercynian basement rocks of the Iberian Meseta (Cunha and dos Reis, 1995; Wilson, 1988). The Lusitanian Basin, mainly composed of Cretaceous and Jurassic sediments with northern pockets of Triassic sediments, is geologically younger than other parts of Portugal and Spain with a heterogeneous mix of lithologies including sandstones and limestones, clays, marls, and some volcanic rocks (Azerêdo et al., 2002; Wilson, 1988: See Waterman, 2012 for more detail). Because it is a carbonate-dominated Mesozoic landscape, Lusitanian Basin sediments should have $^{87}Sr/^{86}Sr$ close to marine values (0.707-0.710: e.g. Schneider et al., 2009). Additionally, as a coastal region, seawater rainfall and sea spray can be incorporated into the terrestrial food chain which may also contribute to $^{87}Sr/^{86}Sr$ values that are close to that of seawater (0.709) (Bentley, 2006). Slightly higher $^{87}Sr/^{86}Sr$ values should be found in some parts due to variations in clastic deposits, and local water analyses have recorded $^{87}Sr/^{86}Sr$ ratios of 0.709-0.711 (Voerkelius et al., 2010). In contrast, the older Palaeozoic Hercynian basement metamorphic and granitic rocks of the Portuguese interior should generally have more radiogenic values ($^{87}Sr/^{86}Sr > 0.713$: e.g. Bea et al., 2003).

## 3. Materials and Methods

### 3.1 Sampled materials

For this study 16 cattle teeth from Leceia and 27 cattle teeth from Zambujal were analyzed. (Table 1). The Leceia samples come from material that is housed in the Centro de Estudos Arqueológicos do Concelho de Oeiras/Câmara Municipal de Oeiras (Bacarena, Portugal), previously studied by Cardoso and Detry (2002). The Zambujal samples are from the von den Driesch and Boessneck faunal assemblage which is currently housed at the Leonel Trindade Municipal Museum (Torres Vedras, Portugal). The Zambujal samples selected are dominated by specimens dated to the early Chalcolithic (c. 3000-2500 cal BC), whereas the majority of our specimens from Leceia were dated to the Full/Late Chalcolithic (c. 2500-2200 cal BC).

Left third molars were prioritized to ensure that each sample was from a separate individual, and one enamel slice per tooth was taken, in order to maximize the number of individuals being investigated. A transversal slice of enamel was cut from the base of the protoconid using a diamond cutter disc coupled to a dentist drill (following the method outlined in Minniti et al., 2014). Only fully formed teeth, with closed roots and which were in wear, were used. This made the location independent from wear, and ensured that the samples were unaffected by any potential age bias. Samples of both enamel and dentine were taken for 18 animals in order to examine any intra-individual variation indicative of relationships between mobility and life history. In order to test for potential effects of sample diagenesis 10 samples were divided during the wet chemistry process and one portion underwent additional washes of acetic acid before further processing.

**3.2 Determining Local Values**

The most established method for estimating the local $^{87}Sr/^{86}Sr$ range for a region is by using the mean of sampled local faunal or human remains ± 2 s.d. to account for the upper and lower limits of the range. Because nonlocal outlier samples can skew the local estimate, tooth and bone samples are best taken from animals with very limited geographic ranges (e.g. rabbits) (Bentley et al., 2004; Price et al., 2002). Plants, water and soil samples can also provide local estimates, but may not provide as accurate of an account of the local bioavailable range as animal tissues. For this study local small fauna (rabbits) and plants were collected and analyzed to help determine the local bioavailable $^{87}Sr/^{86}Sr$ isotope composition at Leceia and to reaffirm the local range for Zambujal that was presented in Waterman et al., (2014).

### 3.3 Wet Chemistry and Mass Spectrometry

All chemical processing of the samples was carried out at the University of Iowa Department of Earth & Environmental Sciences clean laboratory. Details of the laboratory protocol used for this analysis followed the procedures outlined in Waight et al., (2002), see Waterman et al., (2014) for a full description. $^{87}Sr/^{86}Sr$ ratios were measured using a Nu Plasma HR multicollector inductively-coupled-plasma mass-spectrometer (MC-ICP-MS) in the Department of Geology at the University of Illinois at Urbana-Champaign. Samples were introduced to the machine using a Nu Instruments DSN-100 desolvator system equipped with a nebulizer with an aspiration rate near 0.1 mL min$^{-1}$. The samples were alternately run with standards (SRM 987, SCS coral and E&A) using a sample-standard-bracketing measurement protocol wherein standards were run every 3-5 samples (Rehkämper et al. 2004). The $^{88}Sr$ beam intensities for all samples and standards ranged from 4 to 12 V (100 ppb solutions). Masses of $^{83}Kr$ to $^{88}Sr$ were measured during a single cycle comprised of 2 blocks of 25 scans (5 s integration per scan) with a 40 s baseline determination using ESA-deflected signals. Instrumental mass bias was internally normalized to an $^{86}Sr/^{88}Sr$ ratio of 0.11940 and then corrected ratios were normalized to the NIST SRM 987 international standard value of 0.710268 (which had a reproducibility of ± 0.000013: 2 s.d., n=47) to correct for day-to-day variability. No corrections were necessary for Sr introduced as part of sample production as procedural blanks were < 100 pg Sr.

## 4. Results

Results are presented in Tables 1-2 and Figure 3. The 10 separated samples subjected to a more rigorous regiment of acid washes showed negligible differences in Sr values to the control samples (0.00019-0.00003), suggesting diagenesis was not a major concern for the dental enamel. Both sites yielded results with a relatively wide range of enamel values. At Zambujal enamel samples had an $^{87}Sr/^{86}Sr$ range of 0.7054 to 0.7127, while at Leceia the range was wider, from 0.7046 to 0.7179. For Leceia, based upon the sampled leaves and small fauna, the local $^{87}Sr/^{86}Sr$ value range is estimated to be 0.7067-0.7077. For Zambujal the $^{87}Sr/^{86}Sr$ local range was previously defined as 0.709-0.7115 (Waterman et al., 2014). The small fauna and leaves tested in this analysis fell right below the lower end of this spectrum, thus we have adjusted the local range for Zambujal slightly to 0.7085-0.7115. This range fits the majority of the heavily clustered Zambujal fauna in this study. The dentine samples had a much smaller range than the enamel at both sites. As dentine is more likely to be contaminated with the Sr isotope signature from the local soil, or to remodel to the local Sr isotope signature after movement into a new area, this more limited value range was expected. However, whilst at Zambujal all of the dentine values fall within the calculated local range, at Leceia the dentine range is much wider and some samples deviate from the calculated local range. This is an intriguing pattern which will be discussed further below.

**4.1 Enamel values**

The cattle enamel samples from Zambujal and Leceia show some divergence in the $^{87}Sr/^{86}Sr$ ratio with more specimens from each site clustering around the defined local ranges (Figure 3). Using the nonparametric Mann-Whitney U test (due to the non-normal distribution of the data), the differences between the sites are found to be extremely statistically significant (p=0.000) (Table 3). These differences are also demonstrated using box plots in Figure 4. Density plots (Figure 5) also show that cattle from Leceia display a wider range of values than Zambujal, despite having a smaller sample size, indicating that Leceia had a wider catchment area for its cattle.

At Zambujal a number of specimens plot outside of its local range. Those falling above are in the range of 0.712-0.713, but those below are more spread out from 0.705-0.708. Some of these fall within the local range calculated for Leceia (0.706-0.708), but one specimen falls even below this range (0.705). At Leceia a number of specimens have values that are higher than the site's local range. Most of these fall into the Zambujal range, but there is also one very high value (0.7179), well above the local range calculated for either site. There are also some specimens that fall in the region of the lowest values from Zambujal (<0.705), lower than the range from either site. These results highlight the possibility that cattle were being moved between these two sites, but also that some of them must have been brought in from further afield.

**4.2 Dentine and enamel pairs**

For six cattle from Zambujal and three from Leceia both enamel and dentine were sampled from the same animals (this was also attempted for four other individuals, but one sample failed in each case). These dentine and enamel sets were compared in order to look for evidence of lifetime mobility (Table 2, Figure 6).

At Zambujal, all the cattle for which both dentine and enamel samples were taken exhibited very low $^{87}Sr/^{86}Sr$ variation between samples (0.0001-0.0012). Additionally, all of these values fell within the local range for Zambujal. None of these individuals, therefore, show clear evidence of having been moved into Zambujal from outside of the region between the time of enamel formation and dentine remodeling.

At Leceia two of the three sampled cattle exhibited relatively consistent enamel and dentine Sr values. However, these values (on both the enamel and dentine) are all lower than the calculated Leceia local range. For the third animal the enamel value was higher than local Leceia range (0.7084) (close to the low-end of the Zambujal range), while the dentine value was below the local Leceia range (0.7051) (similar in value from the first two cattle). This suggests that this animal grew up in a different region from where it last lived. Additionally one other dentine sample from Leceia (without an associated enamel sample due to machine error) exhibits a Sr value which is fairly high (0.7122), matching some enamel samples from Zambujal. This is a very high value to have been found in this area, and could potentially result from some kind of contamination.

## 5. Discussion

The results from this study indicate that cattle were being moved into, out of, and within the Estremadura region during the Chalcolithic period. This movement likely occurred most commonly within the Estremadura region, and potentially between Leceia and Zambujal themselves, which were two of the most prominent sites in the region. However, the data gathered here suggests that some movement from more distant regions was also occurring.

In general we can organize the Sr values for the tested cattle into 4 broad groups. These groups account for all the sampled cattle with the exception of the outlying sample from Leceia with a very high value of 0.7179. These groups are:

1. Cattle in the range of 0.7085-0.7115 that match local values for Zambujal and sites in the Zambujal region (from Waterman et al., 2014),
2. Cattle in the range of 0.706-0.708 that match local values from Leceia.
3. Cattle in the range of 0.712-0.713 which fall above the values for Zambujal.
4. Cattle in the range of 0.704 -0.706 which fall below local values for Leceia

In the Iberian Peninsula $^{87}Sr/^{86}Sr$ isotope ratio ranges are available for some geological areas based on water, soil, and plant data (e.g. Freitas et al., 2003; Moita et al., 2009; Schneider et al., 2009; Villaseca et al., 2009; Voerkelius et al., 2010), and predictions about likely $^{87}Sr/^{86}Sr$ isotope ratio ranges can be made for other areas based upon the local geologic lithologies. While detailed maps of bioavailable $^{87}Sr/^{86}Sr$ isotope ratios have not yet been completed for Portugal and Spain, a number of archaeological studies, focusing on individual archaeological sites or regions, have been completed in the last decade. These studies provide us with local bioavailable $^{87}Sr/^{86}Sr$ isotope range for a number of places in central and south-west Iberia that we can compare with the data from Zambujal and Leceia (Table 4, Figure 7). By examining these ranges, the diversity of local and regional geology, and the archaeological evidence for exchange networks in the region, we can begin to identify possible cattle origin and movement patterns in the Zambujal and Leceia regions.

Groups 1 and 2: These groups are composed of animals local to Zambujal and Leceia with $^{87}Sr/^{86}Sr$ isotope values of c. 0.707-0.712. These values are consistent with the underlying geology of most of the Estremadura region—mainly Mesozoic or Cenozoic sediments with small pockets of other lithologies. These are the most common types of underlying geology across Europe, and are present in many parts of Iberia. Local value ranges from most sites in the Estremadura region including Leceia and Zambujal (this study) the Zambujal region (Waterman et al., 2014), Bom Santo (Carvalho et al., 2016), and (part of the range of) Rego de Murta (Waterman et al., 2013) all fall into this range. These values are also present in some parts of the Alentejo region, such as at the site of Monte de Cegonha (Saragoça et al. 2016), as well as at a number of Spanish sites, including Valencina-Castilleja (Diaz-Zorita-Bonilla, 2013), and sites near Madrid (Díaz-del-Río et al., 2017). We are therefore unable to rule out the possibility that some of the sampled cattle in this group are, in fact, non-local but from a region with similar local $^{87}Sr/^{86}Sr$ isotope values. However, the most parsimonious approach to this dataset is to assume these are animals raised locally and, as they are most numerous at both sites, that most cattle were raised and consumed locally during this time period.

Group 3: ‘Non-local’ animals with values between 0.712 and 0.713. These are likely to be from an area with underlying Middle to Upper Palaeozoic sediments (Voerkelius et al., 2010). There are multiple areas in Iberia which have this kind of geology, including in southern Portugal in both the eastern Alentejo and Algarve regions, but also in southern Spain as far away as Andalucia. In south-west Iberia the most prominent area with this kind of geology is the Ossa Morena Zone (OMZ) located in southern areas of Portugal and south-west Spain. The range of values here fits with those from La Pijotilla in south-west Spain, which is in this geological zone, but also at some sites near Madrid (Díaz-del-Río et al., 2017). However, in closer proximity the burial sites of Rego de Murta, located (170km) north and east of Zambujal have a calculated local $^{87}Sr/^{86}Sr$ isotope of ~0.711-0.713 (based on small fauna) but many humans and some larger fauna recovered from the burial had Sr isotope values in the 0.713-0.714 range. This suggests that this region could also be a place of origin for animals in the Group 2 category.

Group 4: ‘Non-local’ animals with values which fall below 0.707. These are likely to be from an area with basaltic volcanic rocks such as the Quaternary and Tertiary volcanic rocks or in regions of basic Palaeozoic volcanic rocks. There are some small areas of the southern Estremadura which have the potential for yielding Sr isotope values this low. These are located to both the east and west of Leceia. No Sr isotope values are currently available from these areas, so these can only be considered as a possibility.

These groups and places of possible origin cover all of the cattle except the migrant animal with the very high Sr isotope value at 0.7179. This animal is likely to be from an area with underlying Lower Palaeozoic sediments (Voerkelius et al., 2010). Some areas of the OMZ also have this kind of geology, including parts of Alentejo. Perdigões, which is in this region has the highest local values of any of the sites presented, with a local range of up to 0.7135-0.7145 (Žalaitė et al., 2018). However, the region around Perdigões has very varied geology, and as part of that study baseline samples were taken from a 10 km radius around the site in order to account for this. Some of the values that resulted from this were even higher –up to 0.7184, which indicates that such high values are possible in this area. Waterman et al. (2014) found one human from the Cova da Moura burial near Zambujal to have a Sr isotope value even higher than the outlier animal (0.720), and the Waterman et al. (2013) study on humans from the Rego da Murta burials in the Ribatejo region of Portugal found three individuals who have Sr isotope values in the 0.717-0.720 range. This suggests that another potential place of origin may be from older geologic formations northeast of the Estremadura region.

The presence of raw materials and artefacts at Zambujal and Leceia provide more evidence of the links between the Estremadura and other regions. We know that variscite, slate, amphibolite, arsenical copper ore, and other materials from the Alentejo region (OMZ) commonly made their way into the Estremadura during the Chalcolithic period. Provenance studies based on lead isotope analysis of artefacts from both Zambujal and Leceia have also indicated that their raw materials come from ore deposits found in the OMZ (Gauß, 2013; Gauß, 2015; Müller and Cardoso, 2008). This increases the likelihood that at least some of the individuals from our result group 3 originate from this region.

Finally, some attention should be given to the differences in catchments between these two settlement sites, and why Leceia may have received livestock from a wider area than Zambujal. This is particularly interesting in the light of further isotopic work we have been undertaking in parallel to this study, which has indicated differences in cattle diet between the two sites (Wright et al., in prep). One possibility is that Leceia was geographically better located for contact with outside regions than Zambujal. It is located slightly closer to the Alentejo region, for example, and may have been a first point of contact for people travelling up into the Estremadura region from the south. Leceia is also located much closer to geology that could potentially yield low Sr isotope values, although this must remain a tentative suggestion until more Sr isotope mapping of the region is undertaken. A second option is that these patterns could be related to a temporal trend. As the sample from Leceia is dominated with specimens from Full/Late Chalcolithic layers, whereas the majority of the Zambujal sample is earlier in date. This could be reflecting an increase in cattle mobility through time during the Chalcolithic period, through increased use and consolidation of exchange networks in south-west Iberia. Larger datasets from more sites are needed to be able to investigate this further.

An alternative explanation may be related to differences in husbandry practices between the two settlements. Perhaps Zambujal was more effective at breeding and keeping its own herds than Leceia was, so it had less need to incorporate more livestock from outside regions. This is something that needs further investigation. The local environment surrounding each of these settlements needs to be examined more closely in terms of suitability for cattle production, and more detailed attention needs to be given to the differences in the faunal assemblages between the two sites, tasks which are beyond the scope of this paper.

## 6. Conclusion

This paper provides the results of one of the first strontium isotope studies focusing on cattle remains, animal mobility, and social organization in southern Portugal. Using data on cattle from the expansive Portuguese Chalcolithic (3000/2900-2000 BC) settlement sites of Zambujal and Leceia (Estremadura, Portugal), we provide evidence that cattle were circulating through the region with non-local animals being documented at both sites. Results indicate that cattle at Leceia had a wider catchment area for its stock than Zambujal, with more migrant animals. Domesticated animals would have played an important role in these emerging economies of these sites, and these exchange networks likely overlap with human mobility and the exchange of other trade goods. Thus, these findings have important implications for our understanding of long and short distant trade and regional economic integration. We suggest that it is likely that cattle with non-local Sr values higher that the $^{87}Sr/^{86}Sr$ local range for Zambujal range may have originated in the Ossa Morena Zone as other evidence of direct exchange links with prominent sites in the Alentejo region, such as Perdigões, are documented. However, the origin for the highest $^{87}Sr/^{86}Sr$ values (>0.718) are still being investigated.

Future studies exploring the involvement of animals in exchange networks in Chalcolithic south-west Iberia will require larger Sr datasets, alongside regionally focused zooarchaeological work comparing animal husbandry regimes. While considerably more Sr isotope values are available for prehistoric sites in south west Iberia than were just a few years ago, further research is needed to provide regional baseline maps. To this end, the Australian National University/Griffith University Strontium Basemap Project currently being undertaken by colleagues has great potential for furthering our interpretation of this data set in the future.

**Acknowledgements**

This work was funded through an *Archaeological Institute of America Archaeology in Portugal Fellowship*. Thanks to Silvia Valenzuela-Lamas for useful discussions on Iberian prehistoric animal mobility, and to Mount Mercy Students Matthew Purl and Nicholas Wilson for their help processing samples at the University of Iowa. Also thanks to Craig Lundstrom, Tom Johnson, and Gideon Bartov of the University of Illinois at Urbana-Champaign for their help with the Mass Spectrometry and to the Museu Municipal of Torres Vedras and the Centro de Estudos Arqueológicos do Concelho de Oeiras/Câmara Municipal de Oeiras for allowing access to the material included in this study. Finally, thank you to the two reviewers for their useful comments and suggestions.

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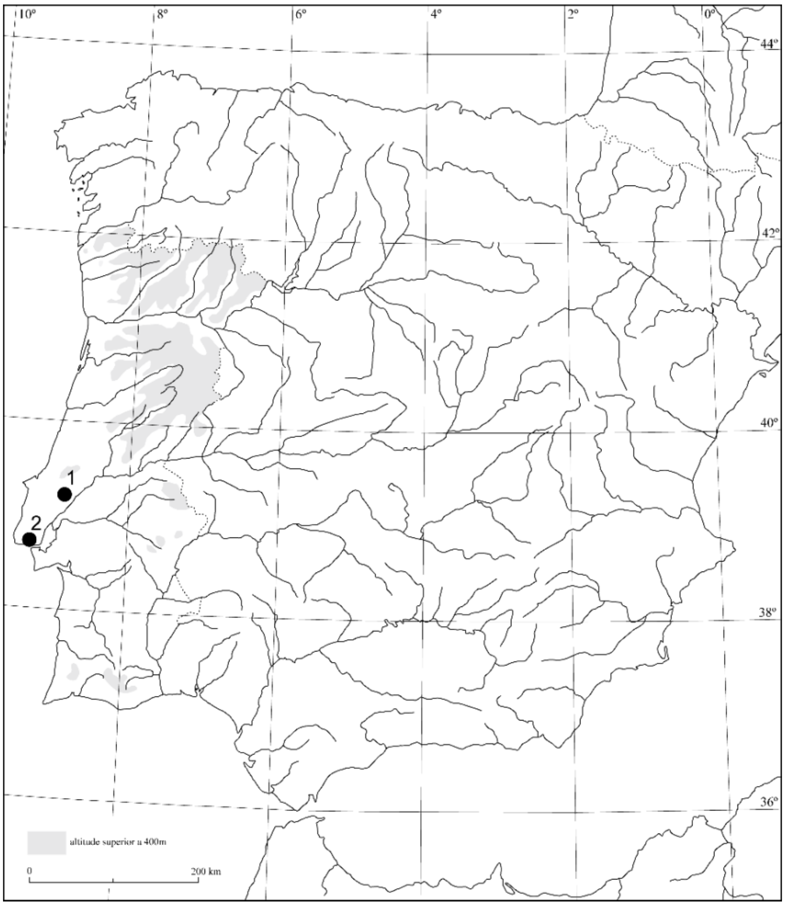


Figure 1: Location of the two sites. 1: Castro do Zambujal; 2. Leceia

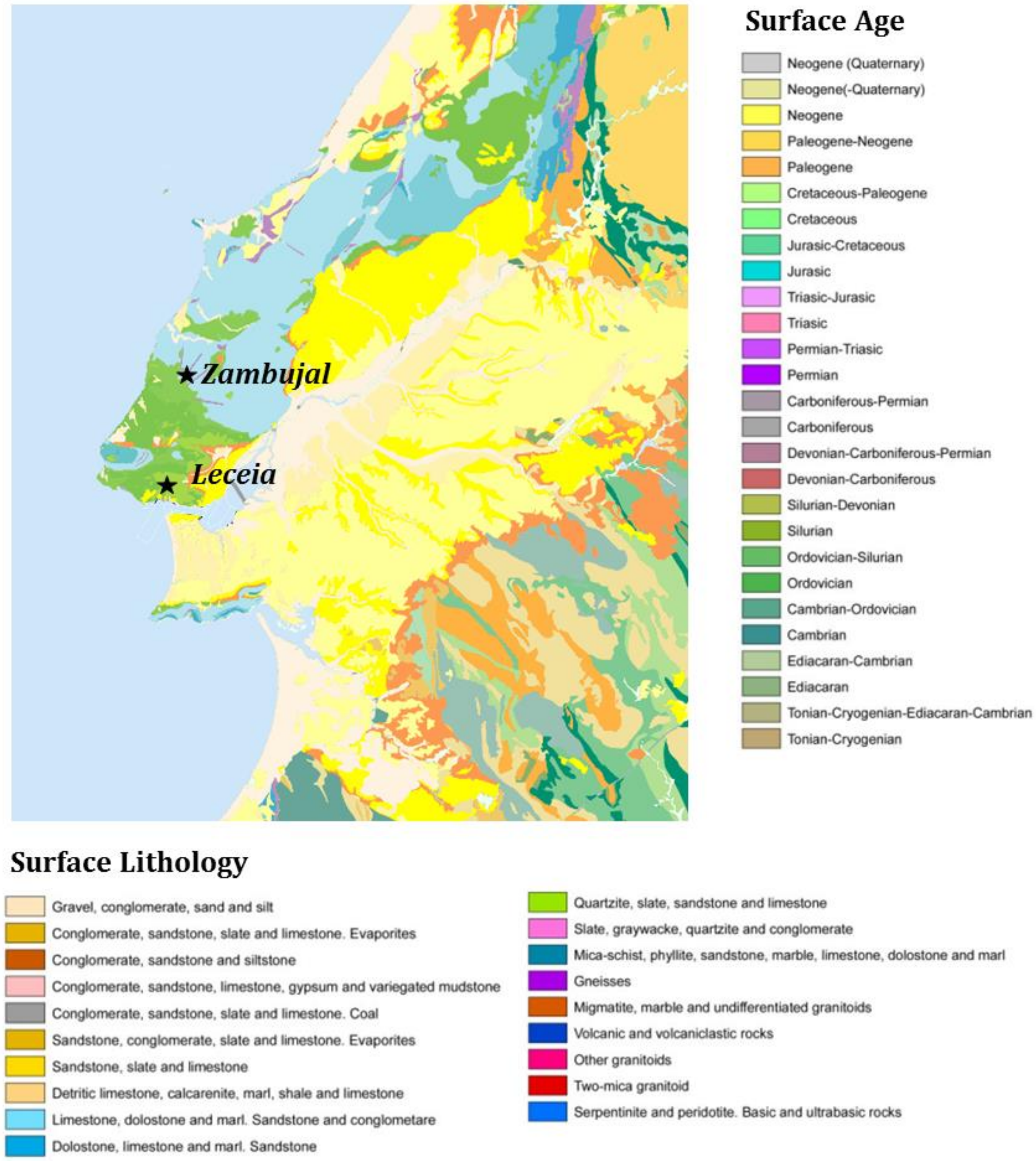


Figure 2: Geological map of the study area

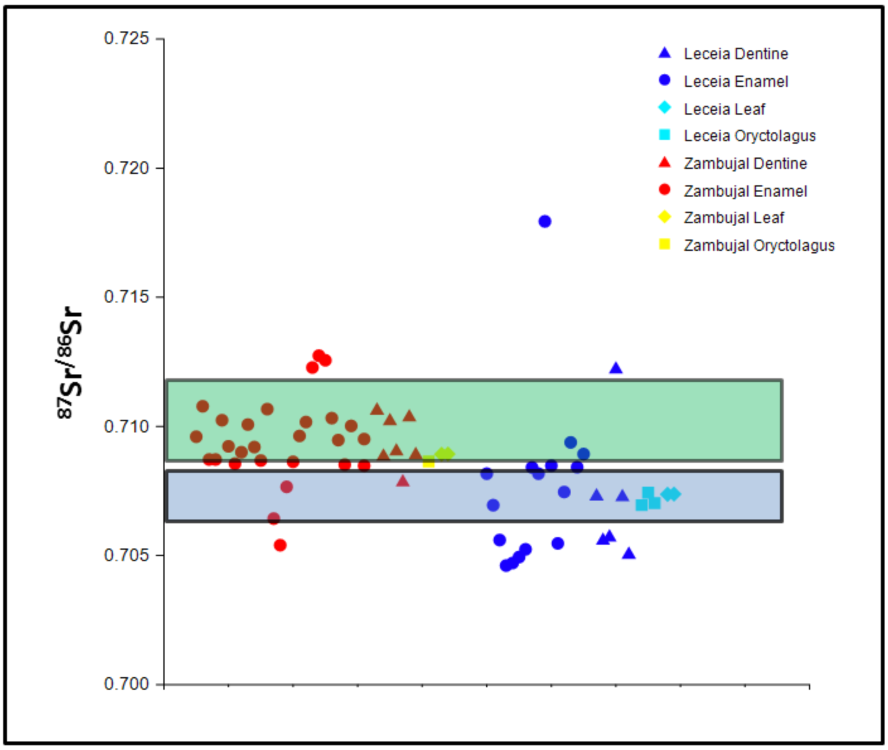


Figure 3: Plot of $^{87}Sr/^{86}Sr$ ratios from cattle teeth (enamel and dentine) at Zambujal and Leceia, alongside ratios taken from locally collected rabbit and plants. The generalised local range for Zambujal is shown in green, and for Leceia in blue.

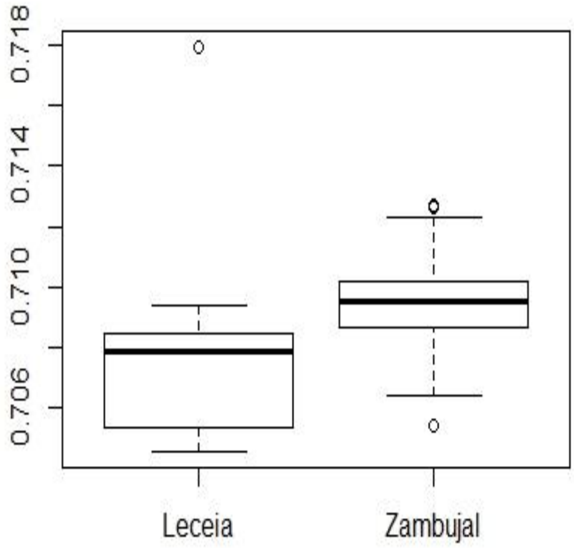


Figure 4: Box-plot comparing $^{86}Sr/^{87}Sr$ enamel values between the two sites

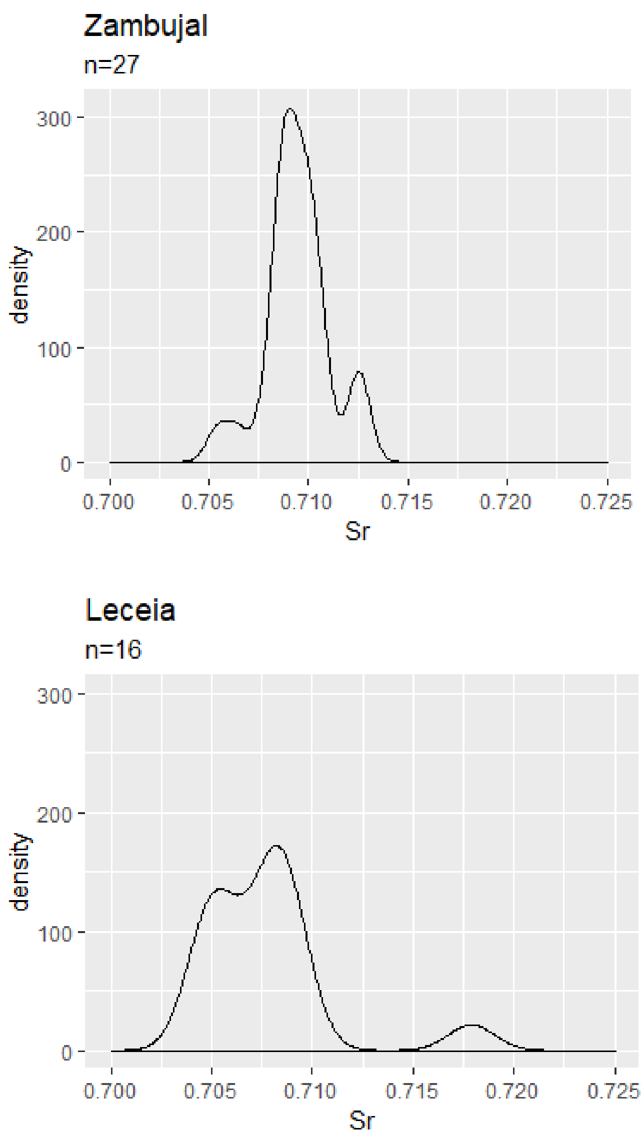


Figure 5: Density plots comparing $^{87}Sr/^{86}Sr$ enamel values between the two sites

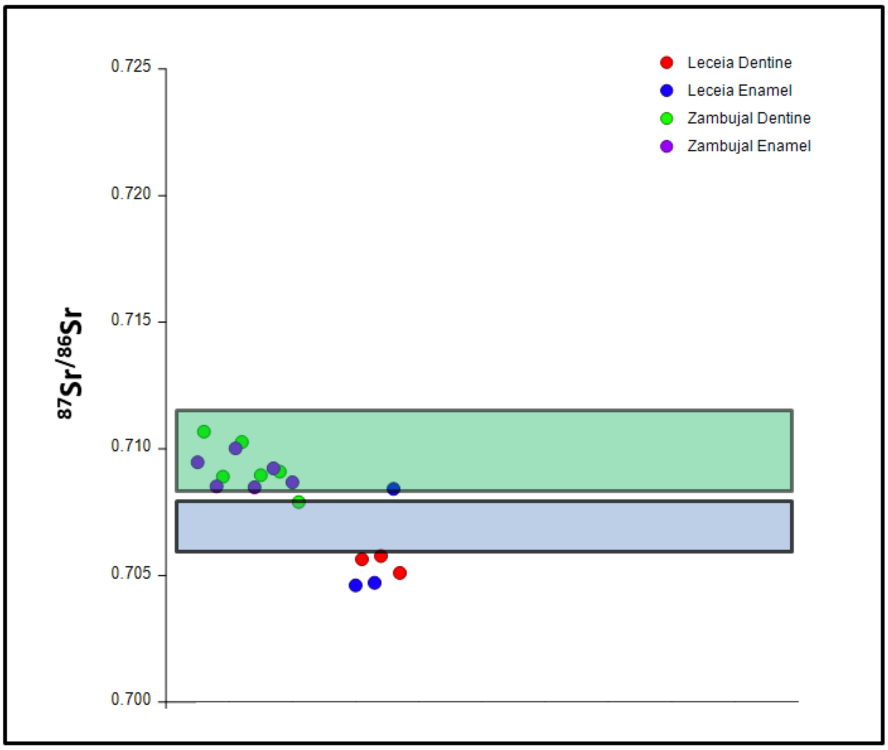


Figure 6: Plot showing $^{87}Sr/^{86}Sr$ values for enamel and dentine pairs.

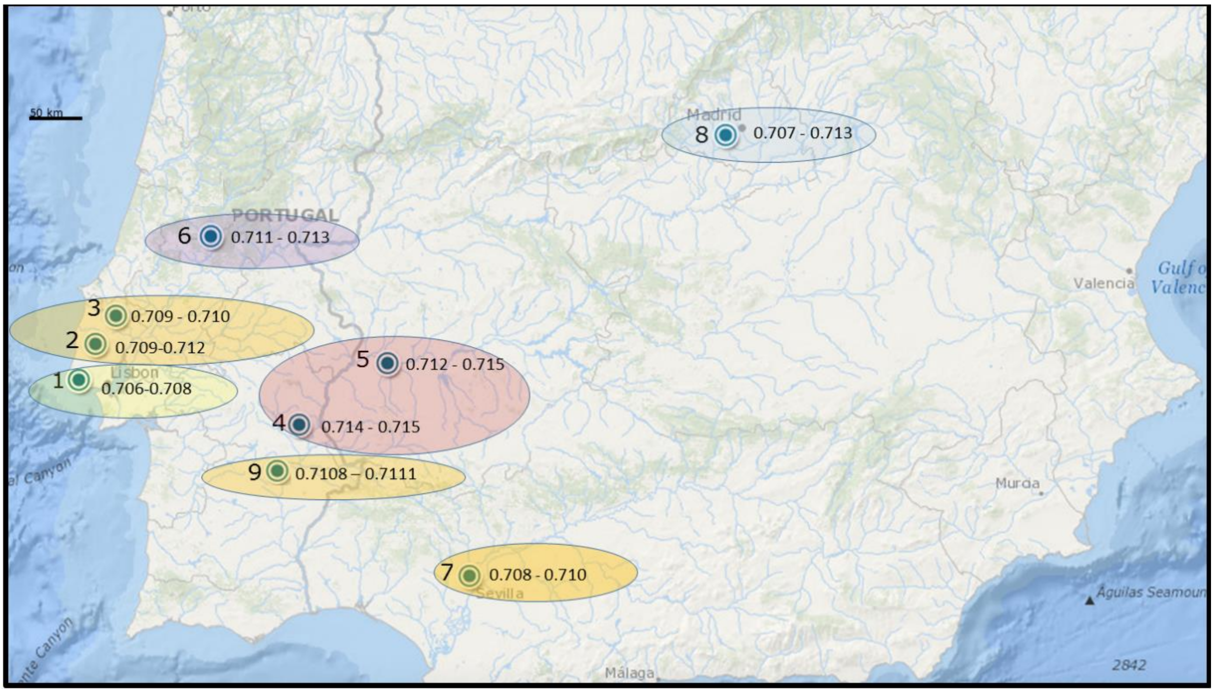


Figure 7: Sites listed in table with $^{87}Sr/^{86}Sr$ ranges. 1. Leceia, 2. Zambujal, 3. Bom Santo, 4. Perdigões, 5. La Pijotilla, 6. Rego da Murta I and II, 7. Valencina - Castilleja, 8. Madrid-region sites, 9. Monte da Cegonha

**Tables**

Table 1: $^{87}Sr/^{86}Sr$ results from all samples

| Site | Genus | Cat # | Type | $^{87}Sr/^{86}Sr$ | Site | Genus | Cat # | Type | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|---|---|---|---|---|
| Zambujal | *Bos* | z807 | Enamel | **0.70960** | Leceia | *Bos* | L8 | Enamel | **0.70817** |
| Zambujal | *Bos* | z1526 | Enamel | **0.71078** | Leceia | *Bos* | L10 | Enamel | **0.70695** |
| Zambujal | *Bos* | z811 | Enamel | **0.70872** | Leceia | *Bos* | L16 | Enamel | **0.70560** |
| Zambujal | *Bos* | z1499 | Enamel | **0.70872** | Leceia | *Bos* | L17 | Enamel | **0.70461** |
| Zambujal | *Bos* | z932 | Enamel | **0.71024** | Leceia | *Bos* | L4 | Enamel | **0.70471** |
| Zambujal | *Bos* | z1051 | Enamel | **0.70923** | Leceia | *Bos* | L19 | Enamel | **0.70494** |
| Zambujal | *Bos* | z886 | Enamel | **0.70856** | Leceia | *Bos* | L27 | Enamel | **0.70524** |
| Zambujal | *Bos* | z000 | Enamel | **0.70900** | Leceia | *Bos* | L1 | Enamel | **0.70841** |
| Zambujal | *Bos* | z1562 | Enamel | **0.71007** | Leceia | *Bos* | L6 | Enamel | **0.70817** |
| Zambujal | *Bos* | z1464 | Enamel | **0.70920** | Leceia | *Bos* | L30 | Enamel | **0.71794** |
| Zambujal | *Bos* | z643 | Enamel | **0.70868** | Leceia | *Bos* | L24 | Enamel | **0.70848** |
| Zambujal | *Bos* | z1524 | Enamel | **0.71067** | Leceia | *Bos* | L9 | Enamel | **0.70547** |
| Zambujal | *Bos* | z68051 | Enamel | **0.70643** | Leceia | *Bos* | L31 | Enamel | **0.70746** |
| Zambujal | *Bos* | z1144 | Enamel | **0.70540** | Leceia | *Bos* | L52 | Enamel | **0.70938** |
| Zambujal | *Bos* | z1225 | Enamel | **0.70766** | Leceia | *Bos* | L2 | Enamel | **0.70842** |
| Zambujal | *Bos* | z591 | Enamel | **0.70863** | Leceia | *Bos* | L7 | Enamel | **0.70893** |
| Zambujal | *Bos* | z803 | Enamel | **0.70963** | Leceia | *Bos* | L20 | Dentine | **0.70736** |
| Zambujal | *Bos* | z62 | Enamel | **0.71017** | Leceia | *Bos* | L17 | Dentine | **0.70564** |
| Zambujal | *Bos* | z778 | Enamel | **0.71228** | Leceia | *Bos* | L4 | Dentine | **0.70577** |
| Zambujal | *Bos* | z68015 | Enamel | **0.71274** | Leceia | *Bos* | L5 | Dentine | **0.71227** |
| Zambujal | *Bos* | z1814 | Enamel | **0.71256** | Leceia | *Bos* | L18 | Dentine | **0.70733** |
| Zambujal | *Bos* | z971 | Enamel | **0.71032** | Leceia | *Bos* | L2 | Dentine | **0.70510** |
| Zambujal | *Bos* | z1168 | Enamel | **0.70947** | Leceia | *Oryctolagus* | L9 | Bone | **0.70695** |
| Zambujal | *Bos* | z1513 | Enamel | **0.70852** | Leceia | *Oryctolagus* | L6 | Bone | **0.70743** |
| Zambujal | *Bos* | z68071 | Enamel | **0.71002** | Leceia | *Oryctolagus* | L3 | Bone | **0.70703** |
| Zambujal | *Bos* | z1181 | Enamel | **0.70848** | Leceia | Leaf | Leaf L1 | | **0.70737** |
| Zambujal | *Bos* | z155 | Enamel | **0.70951** | Leceia | Leaf | Leaf L2 | | **0.70738** |
| Zambujal | *Bos* | z1168 | Dentine | **0.71068** | | | | | |
| Zambujal | *Bos* | z1513 | Dentine | **0.70890** | | | | | |
| Zambujal | *Bos* | z68071 | Dentine | **0.71027** | | | | | |
| Zambujal | *Bos* | z1051 | Dentine | **0.70910** | | | | | |
| Zambujal | *Bos* | z643 | Dentine | **0.70790** | | | | | |
| Zambujal | *Bos* | z1042 | Dentine | **0.71042** | | | | | |
| Zambujal | *Bos* | z1181 | Dentine | **0.70896** | | | | | |
| Zambujal | *Oryctolagus* | z238401 | Bone | **0.70864** | | | | | |
| Zambujal | *Leaf* | Leaf Z1 | | **0.70892** | | | | | |
| Zambujal | *Leaf* | Leaf Z2 | | **0.70893** | | | | | |

Table 2: Results from enamel and dentine pairs

| Site | Genus | Cat # | $^{87}Sr/^{86}Sr$ Enamel | $^{87}Sr/^{86}Sr$ Dentine |
|---|---|---|---|---|
| Zambujal | Bos | z1051 | **0.70923** | **0.70910** |
| Zambujal | Bos | z643 | **0.70868** | **0.70790** |
| Zambujal | Bos | z1168 | **0.70947** | **0.71068** |
| Zambujal | Bos | z1513 | **0.70852** | **0.70890** |
| Zambujal | Bos | z68071 | **0.71002** | **0.71027** |
| Zambujal | Bos | z1181 | **0.70848** | **0.70896** |
| Leceia | Bos | L17 | **0.70461** | **0.70564** |
| Leceia | Bos | L4 | **0.70471** | **0.70577** |
| Leceia | Bos | L2 | **0.70842** | **0.70510** |

Table 3: Results of the Mann-Whitney U test for differences in $^{87}Sr/^{86}Sr$ values between sites

| **Site** | **n** | **W Sum ranks** | **z** | **p** |
|---|---|---|---|---|
| Zambujal | 27 | 738.50 | -3.631 | 0.000 |
| Leceia | 16 | 207.50 | | |
| **Total** | **43** | | | |

Table 4: $^{87}Sr/^{86}Sr$ \`local\` values from sites across central and south west Iberia. *Local values are presented as given in the stated references, but are not always calculated in the same way. All ranges are given to three decimal places, with the exception of Monte Cegonha, which has a very small range.

| # in Figure 7 | Area/site | Local value* | Reference |
|---|---|---|---|
| 1 | Leceia (Estremadura) | 0.706 – 0.708 | This work |
| 2 | Zambujal region (Estremadura) | 0.709 - 0.712 | Waterman et al. 2014, and this work |
| 3 | Bom Santo Cave (Estremadura) | 0.709 - 0.710 | Carvalho et al. 2016 |
| 4 | Perdigões (Alentejo) | 0.714 - 0.715 | Žalaitė et al. 2018 |
| 5 | La Pijotilla (SW Spain) | 0.712-0.715 | Diaz-Zorita-Bonilla 2013 |
| 6 | Rego da Murta I and II (Ribetejo region, Estremadura) | 0.711 – 0.713 | Waterman et al. 2013 |
| 7 | Valencina-Castilleja (SW Spain) | 0.708-0.710 | Diaz-Zorita-Bonilla 2013 |
| 8 | Sites near Madrid, Tagus Basin, (Spain) | 0.707-0.713 | Díaz-del-Río 2016 |
| 9 | Monte Cegonha | 0.7108-0.7111 | Saragoça et al. 2016 |